Electromechanical, Thermal Properties and Radiation Hardness Tests of Piezoelectric Actuators at Low Temperature

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ELECTROMECHANICAL, THERMAL PROPERTIES AND RADIATION HARDNESS TESTS OF PIEZOELECTRIC ACTUATORS AT LOW TEMPERATURE

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Abstract

IPN Orsay participates, in the frame of the CARE project activities supported by EU, to the development of a fast cold tuning system for SRF cavities. The main task of IPN is the full characterization of piezoelectric actuators at low temperature T, and the study of their behaviour when subjected to fast neutrons radiation at T=4.2 K. In order to compare the performance of various industrial piezoelectric actuators, a new apparatus was developed and successfully used for measuring their electromechanical and thermal properties for T in the range 1.8 K-300 K. Different parameters were investigated as function of T: piezoelectric constant, dielectric and thermal properties including heating ΔT due to dielectric losses vs. modulating voltage V_{mod} and frequency f. We observed a decrease of the maximum displacement ΔX of the actuators tested from $\Delta X \sim 40\mu m$ @ 300K down to 1.8µm-3.5 µm @ 1.8K, depending on both material and fabrication process of the piezostacks. Besides, both material and fabrication process have a strong influence on the shape of the characteristics ΔX vs. T dependence. Finally a dedicated facility located at CERI institute (Orléans, France) for radiation hardness tests of actuators with fast neutrons at T=4.2 K was developed and the first beam tests results are summarized.

INTRODUCTION

Superconducting RF (SRF) cavities are very sensitive to small mechanical perturbations due to their narrow bandwidth $\Delta f_{1/2}$. More precisely, high electromagnetic fields induce mechanical deformations (~µm) of the cavity wall, leading to a frequency detuning $\Delta f \approx \Delta f_{1/2}$ of these accelerating structures. In order to reduce this effect, which results other ways in a substantial additional RF power so as to control E_{acc}, the SRF cavities are stiffened. However, the detuning factor K_L reached with stiffened SRF cavities (e.g Δf=- K_L. E_{acc}^2, $K_L \approx$1-2Hz/(MV/m)^2) is still much higher than needed. An alternative strategy or dynamic compensation of Lorentz force detuning, using commercial piezoelectric actuators as active elements for deforming the resonator was successfully applied to TESLA cavities [1]. In this paper, we will report the experimental results on the characterization of piezoelectric capacitive actuators at low temperature (i.e 1.8 K-300K), we obtained recently. Finally we will summarize the first radiation test results with a fast neutrons beam at liquid helium temperature.

EXPERIMENTAL SET UP AND TEST PROCEDURE

A dedicated facility was designed and successfully used for this purpose: the experimental details, measurements method and the first results were presented previously [2]. The actuators tested (Fig. 1) are PZT (Lead Zirconate Titanate) piezostacks from different companies.

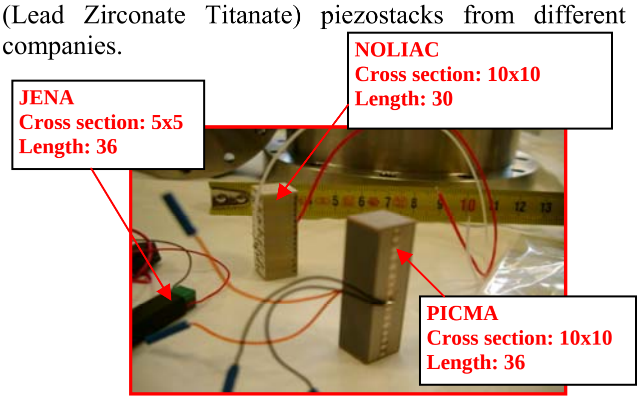

Fig. 1: Piezoelectric actuators tested (Dimensions in mm).

The test-cell (Fig. 2) fulfills the following main requirements:
-calibration and full characterization of piezoelectric actuator under vacuum and at controlled low temperature,
-avoid any shear forces, tilting and/or torsional forces which would damage the piezostacks actuator.

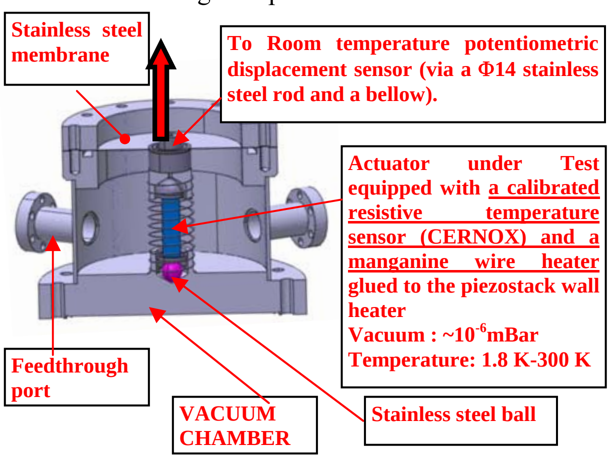

Figure 2: 3D drawing of the test-cell (See [2] for details).

The facility, which was upgraded as compared to the first version [2], operates in temperature range 1.8K–300K and allows automatic measurements of the actuators dielectric, and thermal properties.

RESULTS AND DISCUSSION

Several low voltage actuators (Fig. 1) from different companies (JENA, NOLIAC, PICMA from PI) were tested.

Piezosystem JENA actuators results

Actuators of different production series from piezosystem JENA were investigated [2]. These actuators, which are of the same type (Maximum stroke $\Delta X \approx 42$ µm @ T=300 K, calibration curve given by JENA), were rejected because of five main drawbacks and limitations:

1) Maximum stroke less than 2 µm at 2K (3 µm are required),
2) Insufficient blocking force : ~1kN @ 300K (3kN are required),
3) Low mechanical stiffness: 25N/µm (100 N/µm are required),
4) Lack of fabrication reproducibility from batch to batch (i.e. different behaviour of ΔX vs. T),
5) Very short lifetime when operated at 2 K (electrical breakdown and/or mechanical damages).

The experimental data previously reported (JENA #9221[2]) show that for these actuators ΔX decreases strongly with T from 42 µm @ 300 K down to 2 µm @ 2K. For these actuators, the measured variations of the loss factor tg(δ) at 100Hz as function of T show a peak around T~10K-20K. As a consequence, when the actuator is subjected to a sine voltage, the dielectric losses P_{diel} versus T curve shows also a broad maximum around T ~10K-20K. For a sinusoidal displacement of 1µm amplitude at a frequency of 100 Hz, the thermal load to 1.8K is lower than 1 mW.

PICMA actuators results

These prototypes actuators from PI are not calibrated. We used JENA actuators and the displacement sensor for the calibration of PICMA (Fig. 3) and NOLIAC actuators. These data show the well known hysteresis @ 300K with a maximum stroke of 40 µm @ V_{max}=120V. Note that this hysteresis is completely negligible for T< 4.2 K.

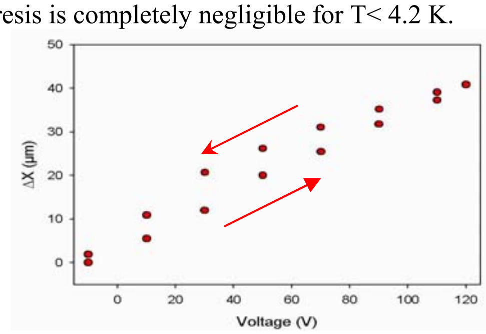

Figure 3: Displacement vs. Voltage actuator PICMA#1@ 300 K.

The variations of the maximum expansion ΔX for the actuator PICMA#1 with temperature are shown in Fig. 4.

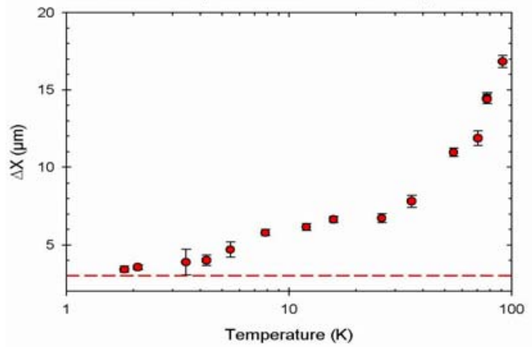

Figure 4: Variations of the full range (V_{max}=120 V) displacement with temperature (Actuator: PICMA#1).

Again, these data show a strong decrease of the slope of ΔX vs. T curve with temperature. This behavior seems to be mainly due to the strong dependence (Fig. 5) of Cp on T. Note that the maximum stroke ΔX is decreased by a factor of ~13 when T decreases from 300 K down to 2 K and this result is in the range of values reported previously by other authors.

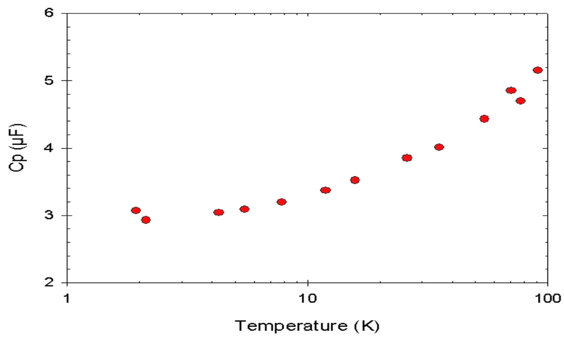

Fig.5: Actuator capacitance versus temperature.

Moreover, at low temperature (i.e. T≤100 K), we notice (Fig. 6) a linear relationship between ΔX and the parallel capacitance C_p (i.e. $\Delta X \propto C_p$). This behavior, similar to that observed for JENA piezostacks [2], gives a straight-forward mean to calibrate actuators. Indeed, capacitance measurements are more simple and less time consuming, as compared to a true calibration (i.e. ΔX vs. T) and specially for a large number of actuators (e.g. ~1000 for XFEL).

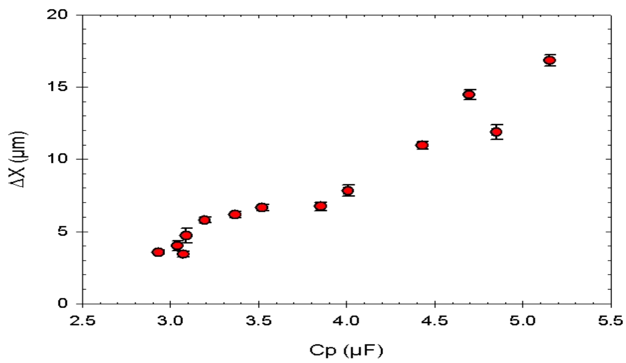

Figure 6: Full range displacement versus capacitance.

Dielectric and thermal properties

Measurements of the following parameters were performed for T ranging from 1.8K to 300K: a) dielectric properties (Cp, complex impedance: Z, and tg(δ) @ 100Hz, 120 Hz and 1kHz), heating ΔT vs. sinusoidal voltage amplitude V_{mod} and frequency f, b) thermal properties (Specific heat: C_{th}, thermal resistance: R_{th} and time constant $\tau= R_{th}.\, m.C_{th}$, with m: actuator mass).

The dielectric constant ρ_r of the material vs. T, which is deduced from Cp, is obviously homothetic to the curve of Fig.5: ρ_r decreases from 1454 @300K to 328 @1.8K. The heating ΔT versus time when the actuator is subjected to a sinusoidal voltage (T=1.8K) is shown in Fig. 7.

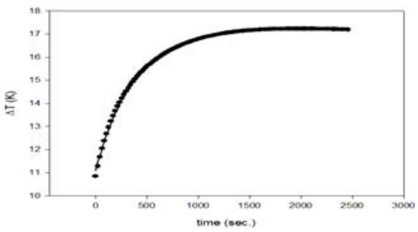

Fig. 7: Dielectric heating ΔT of the actuator @ T=1.8 K (sinusoidal voltage : V_{mod}=1.5 V, f=100 Hz).

These data clearly show an exponential dependence on the time t: $\Delta T= \Delta T_{max}.(1-\exp(-t/\tau))$. The fit to the data leads to the following values: τ=376 s, $R_{th}=9.10^5$mK/mW and $m.C_{th}=4.310^{-4}$ J/K. Note that V_{mod} corresponds to a displacement of 170 nm of the cavity wall (i.e. frequency shift Δf=68 Hz) with total dielectric losses P_{diel}= 20 µW and heating ΔT=17K (steady state value: Fig. 7). Moreover, the heating ΔT vs. modulation voltage amplitude and frequency is shown in 3D plot (Fig. 8). The observed heating (i.e. $\Delta T=R_{th}.P_{diel}$) is well described by the well-known expression of the total dielectric losses P_{diel} (i.e. $\Delta T \propto P_{diel} = \pi.f.Cp.V_{mod}^2.\sin(\delta)$). Note that the small departure from the quadratic dependence observed at high modulation voltage amplitude and/or frequency, is attributed to nonlinear effect resulting from Cp and sin(δ) dependence on T.

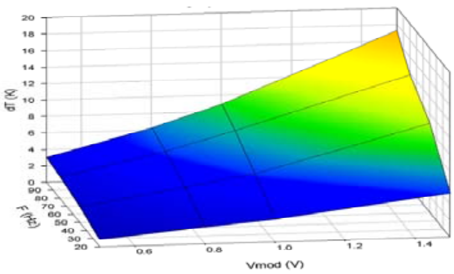

Figure 8: 3D plot o vs. heating modulation voltage amplitude and frequency.

Irradiation with fast neutrons at T=4.2 K

Furthermore, four PICMA and four NOLIAC actuators were subjected to irradiation tests (Fig. 9) at T=4.2 K with a fast neutrons beam (Energy spectrum: 1-15MeV). A total dose of $1.8.10^{14}$-$3.1.10^{14}$n/cm^2 (activation of high purity Ni foils measurements) was achieved in 20 hours: neither damage nor anomalous behavior or performance degradation of these actuators were observed. We have recorded only C_p increase, which are probably due to a thermal effect (i.e. heating with neutrons).

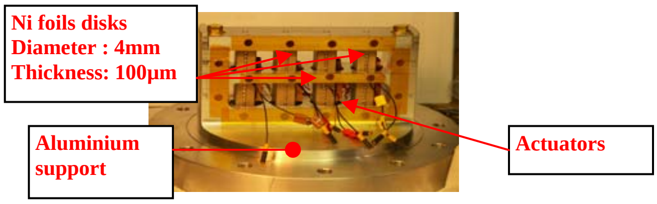

Fig. 9: Four PICMA actuators equipped with Ni foils prior to the test

CONCLUSION AND OUTLOOK

A dedicated apparatus was developed for full characterization of piezoelectric actuators at low temperature 1.8 K-300 K. Several PZT actuators from three different companies were fully characterized: ΔX decreases strongly with T from ~40 µm @ T=300 K down to 1.8 µm -3 µm @ T=1.8 K. The shape of ΔX vs. T curve depends on the actuator material and fabrication process. For actuators of PICMA and NOLIAC type, ΔX=2.8µm-3µm @1.8K leading to a theoretical detuning compensation Δf≈1kHz for TESLA nine cells cavities. The dielectric losses of JENA actuators, for a sinusoidal (f=100 Hz) displacement of 1 µm amplitude at 1.8 K, are lower than 1mW. Furthermore, four PICMA and four NOLIAC actuators were subjected to irradiation tests at T=4.2 K with a fast neutrons beam: for a total dose of $1.8.10^{14}$-$3.1.10^{14}$n/cm^2 neither damage nor anomalous behavior or performance degradation of these actuators were observed. Data show a slight increase of C_p, which are probably due to a thermal effect. A detailed report on irradiations tests will be published when data analysis is completed. Finally, the actuators will be integrated in a cold tuning system for TESLA cavities and tests will be performed soon in the horizontal cryostat facilities CRYHOLAB at Saclay and CHECHIA at Desy.

ACKNOWLEDGEMENT

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